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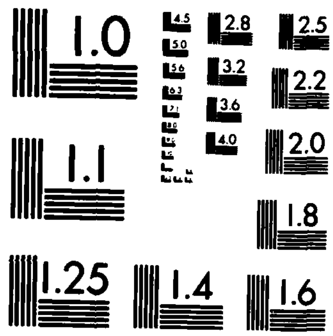

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Monterey, California

THESIS

AN OBJECTIVE DETERMINATION OF
TROPICAL CYCLONE WARNING POSITION

by

William Thomas Curry

June 1985

Thesis Advisor: R. L. Elsberry
Co-Advisor: J. C. L. Chan

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A technique has been developed to determine objectively the location of a tropical cyclone at warning time and reduce the short-term forecast errors due to errors in the warning position. The western North Pacific CLIPER (CLImatology and PERsistence) forecast scheme is used to generate a potential track from each fix, and a smooth curve is fit to the future and past positions. When multiple fixes are available, weighting functions are

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An Objective Determination of Tropical Cyclone Warning Positions

by

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Submitted in partial fulfillment of the requirements for the degree of

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procedure is similar to the approach in determining the "official best track" after completion of the storm. WBT positions at -6 h, -12 h, -18 h, and -30 h are sent to the Fleet Numerical Oceanography Center (FNOC) to generate the various climatological and dynamic forecast aids that are used in preparing the warning position and future warning track. The +6-h forecast positions from the objective aids are blended with the most recent fix positions to determine the "current warning position". Greater confidence should result since extrapolated tracks from each fix are not the only information utilized to establish the warning position. Rather, the forecast tracks from the various aids provide a kind of hindsight for judging the likely accuracy of each fix. Subjectivity still enters the procedure during the blending process. The Typhoon Duty Officer (TDO) must consider the likely accuracy of the fixes from the various platforms (satellite, aircraft, radar or synoptic) in determining the optimal warning position based on his experience and recent platform performance, i.e. which platform has given the best indication of recent storm movement. The TDO has available one to 15 fix positions during the six hours since the previous warning.

The goal of this thesis is to develop an objective procedure for the TDO to use in determining the initial warning position. The strategy for the objective warning position determination proposed here is based on the idea that it is often easier to determine which of the storm center fixes to accept if the forecaster knows the future track. That is, hindsight often allows the forecaster to select more intelligently from a number of possible fix positions. The TDO might then use the warning position from the objective scheme as a "first-guess" position. This position is then adjusted to reflect consistency with the synoptic reasoning that forms the basis for the forecast

II. PROCEDURES OF THE OBJECTIVE TECHNIQUE

Objective initial positioning has been proposed by Morford (1979) as an essential step in improving the short-term (less than 24-h) forecasts at JTWC. Simpson (1971) had earlier proposed a decision-tree format for establishing the initial warning position. This decision-tree approach attempted to use objective aids and similar reasoning in each forecast cycle to insure consistency. However, Simpson's technique was subjective rather than objective. The objective scheme proposed here simulates hindsight by estimating the future positions associated with each fix through an economical and viable short-term forecast technique, the western North Pacific CLIPER, described below.

The western North Pacific CLIPER (CLImatology and PERsistence), which was developed by Xue and Neumann (1984) at the National Hurricane Center (NHC), uses regression equations to relate future storm displacement (DISP) to eight basic environmental predictors:

$$DISP = f(Xo, Yo, U_{-12}, U_{-24}, V_{-12}, V_{-24}, W, D)$$

Xo = Initial longitude

Yo = Initial latitude

U_{-12} = Previous 12-h east-to-west translation

U_{-24} = Previous 24-h east-to-west translation

V_{-12} = Previous 12-h south-to-north translation

V_{-24} = Previous 24-h south-to-north translation

W = Initial maximum wind speed (kt)

D = Julian date.

Note that westward and northward translations are defined to be positive as the typical cyclone track is toward the northwest in the western North Pacific.

current Julian date/time are input to CLIPER to generate a 72-h forecast. Since the goal is an improved initial warning position, only the 12-h and 24-h forecast positions are calculated. However, the 36-h through 72-h track is available if the complete forecast is desired. Linear interpolation is used to derive CLIPER forecast positions at +6 h and +18 h from fix time.

TABLE 1

Empirically-derived weighting factors applied when determining a smooth working best track

	Time (Hours)				
	-24	-18	-12	-06	00
Weight:	20	15	15	10	10

A fourth-order polynomial fit of the future CLIPER warning positions (W+6 to W+24) and prior (00 to W-24) WBT positions is used to determine a smooth estimate of the storm movement. The polynomial routine allows for user-specified weights at each fitted position. Different order polynomial fitting will be included as an option to be selected by the TDO in the interactive version of the scheme. Larger weighting factors (Table 2) are given to the prior positions to assure a smooth evolution from these relatively well-known positions. Separate polynomial fitting of the latitude and longitude positions with time was adopted as an alternative to fitting the time sequence of latitude/longitude pairs. These time-dependent, fourth-order polynomial coefficients are used to determine the tentative warning position (the +6-h position in Fig. 2.1). Notice that the fix position (A) is not included in the polynomial routine. If the fix is close to the previous warning time or an erroneous fix is encountered, a large

When more than one fix is available, a weighted average of the interpolated positions (position D in Fig. 2.2) gives the first iteration of the warning position. The procedure for determining the weights given to different types of fixes will be described in Section 2C. Up to 10 fixes may be included for each warning position determination.

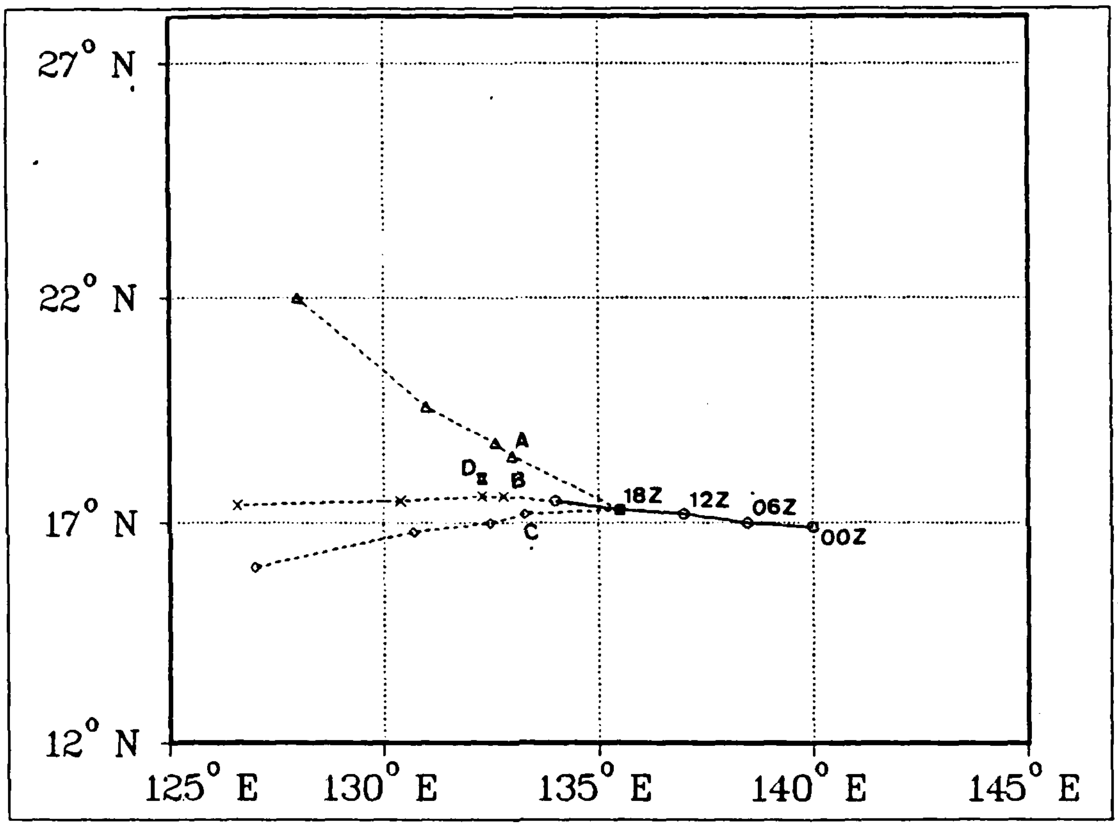

Fig. 2.2 Determination of warning position (D) with with three fixes available. A,B,C are fix positions; 'o', working best track.

Consideration is also given to the potential impact of positioning errors of the fix platforms. In a second iteration, four adjacent positions are generated from the first iteration warning position (point D in Fig. 2.2) by adding an "observational error" in each cardinal direction (Figs.

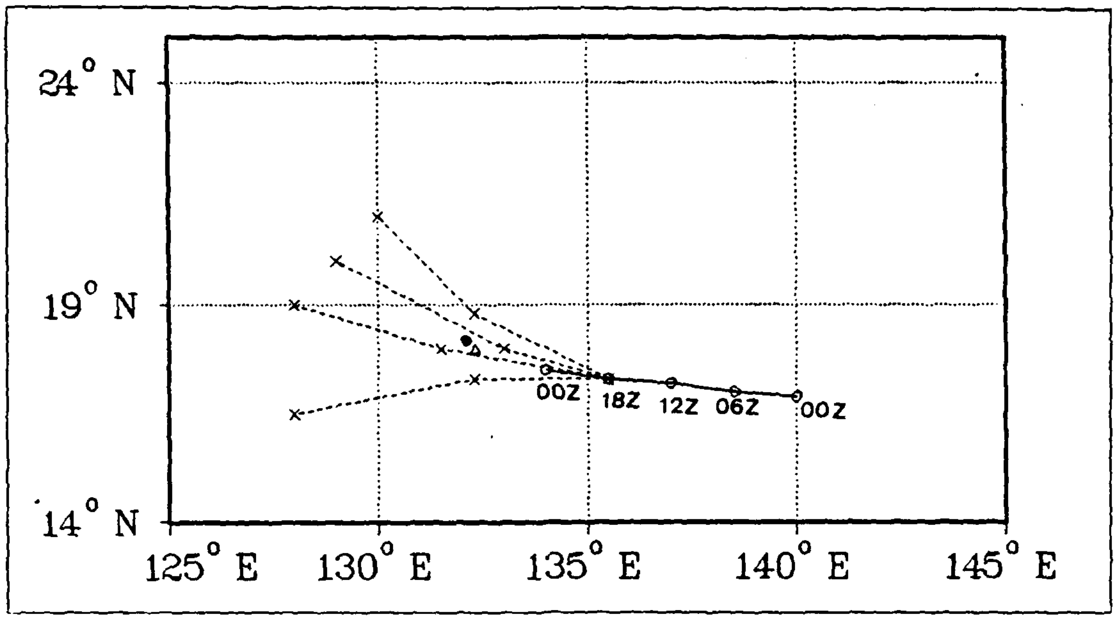

Fig. 2.3b Second iteration of the objective warning position '•'.

TABLE 3

Weighting factors when fitting the second iteration warning position

	Time (Hours)									
	-24	-18	-12	-06	00	+06	+12	+18	+24	+30
Weight:	25	75	45	45	20	15	5	1	1	1

B. INITIAL WARNING PROCEDURE

A special procedure is necessary to start the objective technique with a new storm since the prior "working best track" positions required as input to CLIPER are not available. To generate CLIPER forecasts for the first four warnings, a 24-h history must be developed. All that is required in the objective procedure is a fix about 6 h prior to the first warning time, e.g. a synoptic fix determined by

TABLE 4

Grouping of the fix platforms for determining accuracy from 1981 - 1983 fixes

Satellite:	PCN 5 and 6	(loose organization)	
	PCN 3 and 4	(well defined organization)	
	PCN 1 and 2	(eye present)	
Aircraft:	Group	Navigation accuracy	Meteorological accuracy
	<7<9	< 7 n mi	< 9 n mi
	<7>9	< 7	> 9
	>7<9	> 7	< 9
	>7>9	> 7	> 9
Radar and Synoptic			

used with all storms during 1981- 1983 to extract the medians and standard deviations as potential weighting factors for each fix type. To determine the fix accuracy, the time difference between the last known position and the latest fix (hours and minutes) is converted to a percentage of the 6-h increment. This percentage is then used to linearly interpolate the point along the BT that corresponds to the fix time. The distance between the fix and this corresponding BT position then determines the fix accuracy.

Table 5 is a list of the means, medians and standard deviations for the 1981-1983 storm seasons. Ill-defined storms, multiple centers, upper-lower layer cloud signature decoupling, etc., in a small percentage of fixes contribute to large displacements from the official BT. These outliers serve to shift the distribution and bias both the means and the standard deviations. Thus, the median in each group is chosen as a more satisfactory measure of accuracy. As shown in Table 5, the distinction between the 3-yr average median of the most accurate fix platform (Aircraft <7 <9) and least accurate (Satellite, PCN 5 & 6) is only a factor of three. To provide more discrimination between fix types, a third power of the median is utilized.

TABLE 5
Accuracy of fixes (n.mi.) during storm seasons 1981-1983. A slash (/) indicates insufficient sample size and (*) indicates storms with anomalous errors biasing the statistics.

	1981			1982			1983		
	MEAN	MEDIAN	STD DEV	MEAN	MEDIAN	STD DEV	MEAN	MEDIAN	STD DEV
				SATELLITE					
PCN 5&6	25.8	19.9	24.1	21.1	17.9	16.4	*42.7	18.5	*131.5
3&4	13.4	12.0	9.3	12.2	10.3	8.9	*82.4	12.3	*235.6
1&2	10.0	8.5	7.9	9.6	8.5	6.0	9.8	8.4	7.2
ACCY				AIRCRAFT					
<7<9	8.9	7.5	6.3	7.9	6.3	6.8	*27.8	6.5	*147.5
<7>9	10.6	8.0	9.8	18.6	10.8	19.0	9.3	/	10.6
>7<9	15.5	10.0	27.5	8.2	6.2	8.4	16.8	7.3	68.6
>7>9	15.6	9.2	21.2	12.0	6.9	10.8	*63.2	13.5	*226.7
				RADAR					
	14.1	11.4	15.0	13.1	9.2	13.5	*20.7	7.9	*93.7
				SYNOPTIC					
	12.4	/	8.9	12.6	/	12.1	/	/	/

3-YEAR MEDIAN

SATELLITE PCN		AIRCRAFT ACCY		RADAR	SYNOPTIC
5 & 6	18.8	<7<9	6.8	9.5	N/A GROUPED WITH RADAR
3 & 4	11.5	<7>9	9.4		
1 & 2	8.5	>7<9	7.8		
		>7>9	9.9		

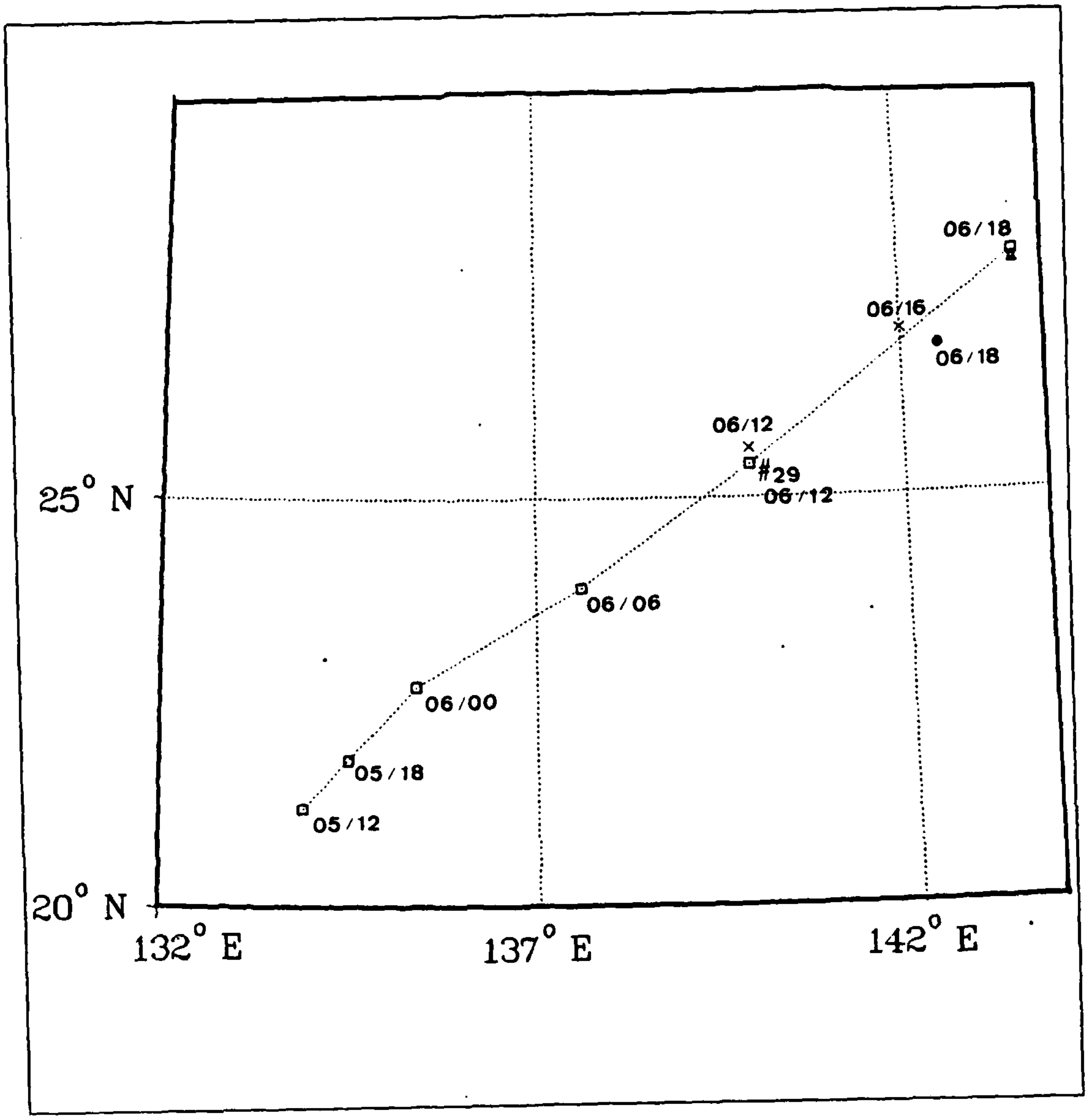

Fig. 2.4 Warning No. 29 Typhoon Marge (1982) illustrating an error in objective warning position due to exclusion of a time bias. '□', best track; '×', fix position; '•', objective warning position; '⧗', JTWC warning position

warning position is determined based on a rhumbline course and speed (dashed line in Fig. 2.7) between the fix and the BT position 12-h prior to the desired warning position. Using the prior 12-h rather than the 6-h position minimizes radical extrapolation angles that might occur if the fix

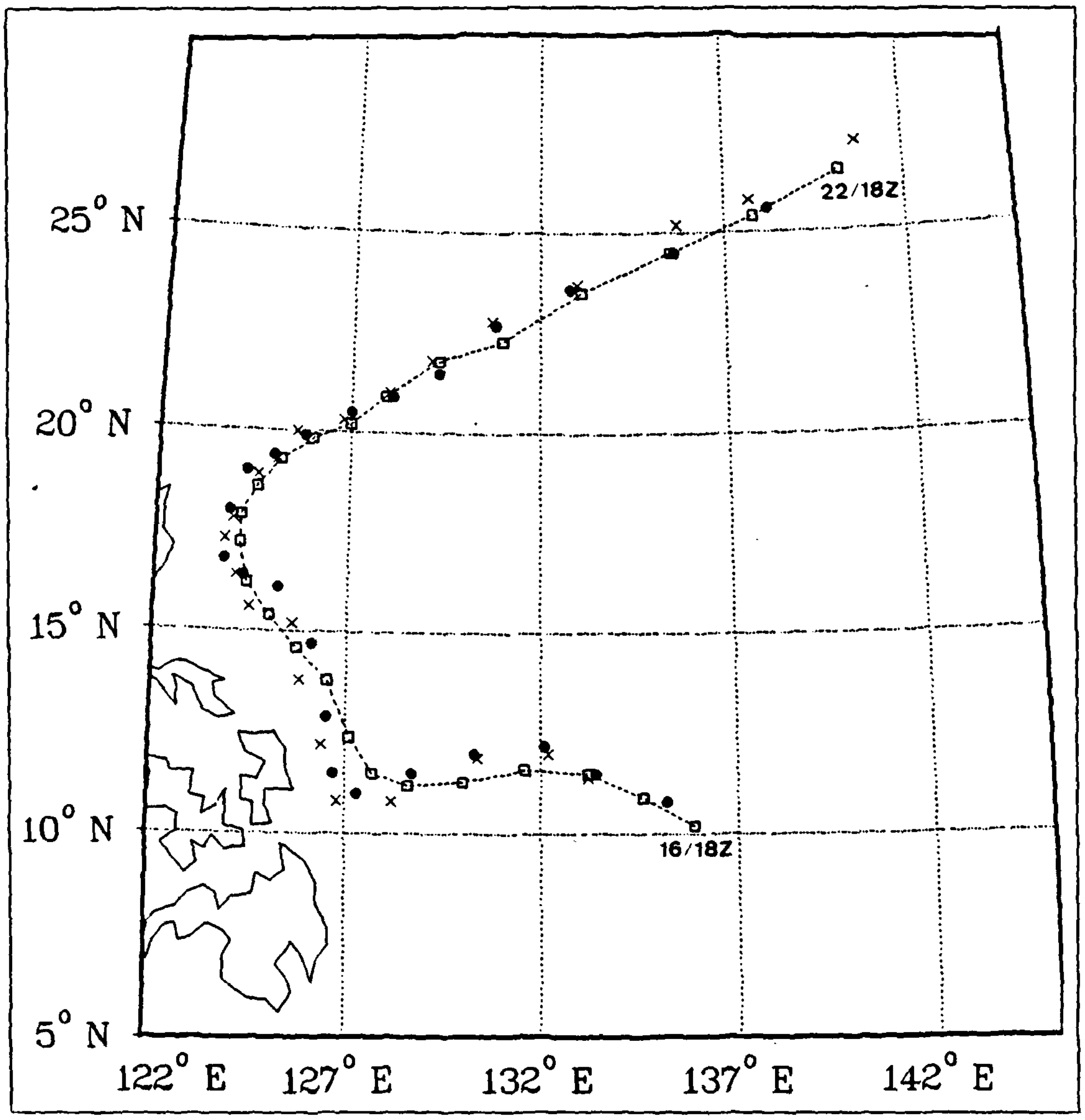

Fig. 2.6 Overall track of Typhoon Pat (1982) from 16 May through 22 May. '□', best track position; '×', JTWC warning position; '●', objective warning position

polynomials would require additional positions to develop the smooth curve and tend to add complication without significant improvement.

TABLE 6

Average warning position error (n mi)
with 3rd or 4th order polynomial curves

Storm	No. of Warnings	JTWC	Polynomial Order 3rd	4th
TY Pat (82)	24	24.9	19.3	18.4
STY Abby (83)	50	11.1	16.0	15.0
TY Thad (81)	28	25.6	26.3	26.1
TY Marge (83)	30	18.4	24.1	23.1
TY Gordon (82)	37	15.5	16.3	15.4
TS Herbert (83)	10	14.3	12.6	12.7
TY Bill (81)	16	18.7	18.9	17.3
TY Dot (82)	31	17.1	20.3	18.7
Total	226			
Weighted Average		17.6	19.4	18.4

and the +6-h forecast generate better results in six out of the eight storms in the test data base (Table 7). This increase in accuracy of initial warning position is consistent with the expected importance of persistence.

Table 8 is a list of the average warning position errors after inclusion of the time bias (Section 2C). The early forecast position weighting emphasis in Table 7 was adopted for these tests. All eight storms had reduced warning position errors when the time weighting factor in Fig. 2.5 was included.

III. RESULTS AND DISCUSSION

In this section, the objective technique will be compared to JTWC's procedure with respect to the average warning position error and the resulting 24-h forecast position. Several storms will be highlighted to illustrate the strengths and weaknesses of the objective scheme. A stratification of the storms by intensity will also be illustrated.

Subsequent to the testing phase (described in Section 2D), 22 additional storms were run for a total of 637 independent warning positions. Inclusion or exclusion of a particular storm from the three-year data base is based on the following constraints:

(1) A fix position 6 h prior to the first warning (to initiate the objective technique) must exist;

(2) Since the current objective technique is limited to 10 fixes per warning, storms with a large number of radar fixes per warning were not included;

(3) Storms with a majority of their path outside the latitude/longitude domain of the CLIPER regression equations were not used; and

(4) Several storms that were either short-lived or included periods of time during which JTWC warnings were unavailable were not included.

TABLE 9

Summary of warning position errors (n.mi.) for JTWC (JT) and objective (OBJ) for the 8-storm test data base. A win (W), tie (T) or loss (L) for the objective technique is indicated and the Student-t score is given.

Storm	No. of Warnings	Avg. JT	Avg. OBJ	Std. Dev. JT	Std. Dev. OBJ	WTL	t
TY Dot (82)	31	20	20	13	14	T	-.11
TS Herbert (83)	10	18	16	10	5	W	-.44
STY Abby (83)	50	11	13	10	9	L	.81
TY Pat (82)	24	27	18	16	10	W	-2.47*
TY Thad (81)	28	26	27	31	36	L	.20
TY Marge (83)	30	20	22	17	18	L	.27
TY Gordon (82)	37	15	14	10	9	W	-.67
TY Bill (81)	16	19	15	13	12	W	-.84
Total	258						
Weighted Average		18.5	17.9	14.8	14.4		

* Difference between the objective error and JTWC official error is significant at 95% confidence level

storms in 1983 had smaller standard deviations. The Student-t test is made for each storm to test whether the difference between the objective warning position error and that of the JTWC is significant at the 95% confidence level. For the 22-storm independent data base, only Typhoon Nelson (1982) would have had significant reductions in warning position error if the objective technique had been used. However, the warning positions of Tropical Storm Ben (1983), Super Typhoon Forrest (1983) and Tropical Storm Georgia (1983) would have been significantly degraded. Examples from these four storms and others of the 22-storm sample will now be examined to determine when the objective technique should or should not be expected to provide accurate initial position guidance.

Fig. 2.6 indicates the relationship of the official BT, the JTWC warning positions and the objective technique warning positons for Typhoon Pat (1982). The objective technique performs very well during the recurvature (change of a dominant northwest to northeast movement around the

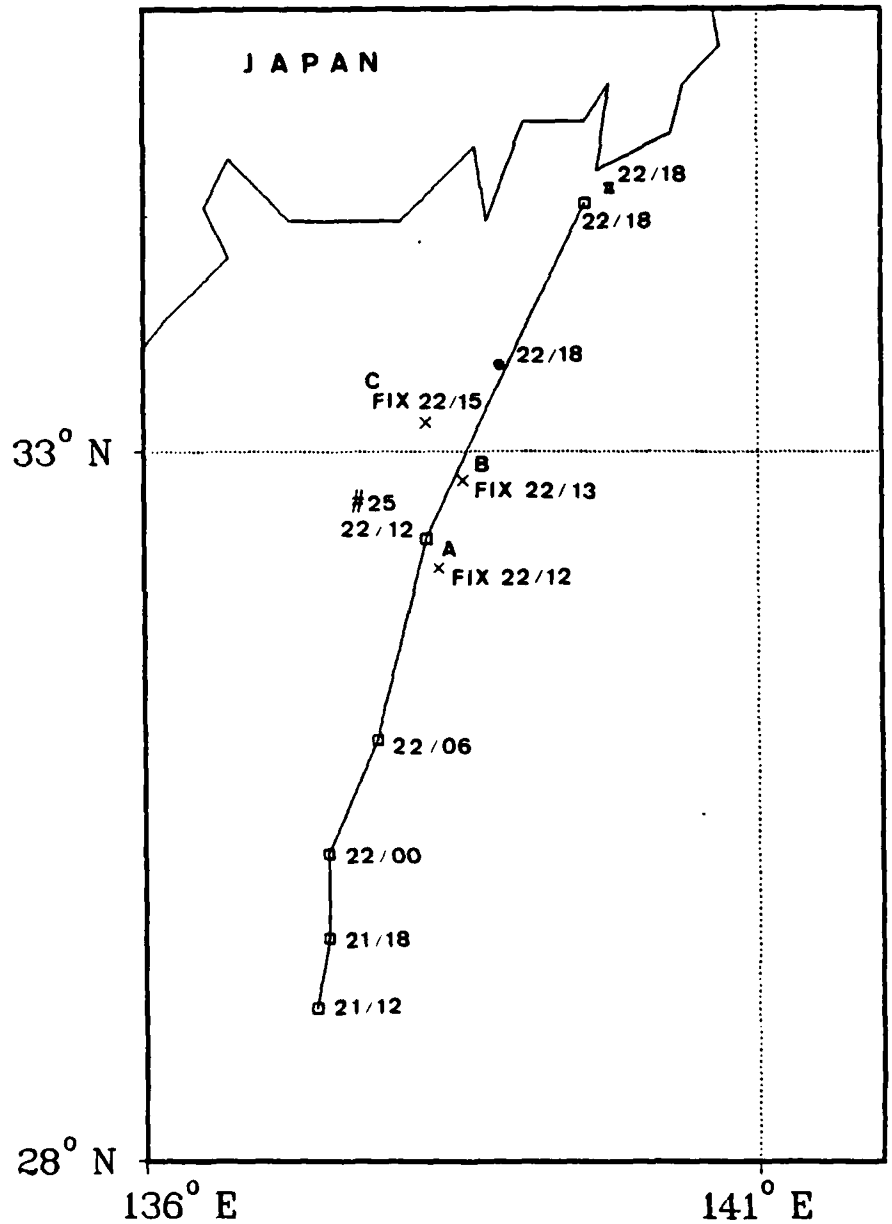

Fig. 3.1 Warning No. 25 of Typhoon Thad (1981). Example of forecast problem when rapid acceleration follows a slow recurvature path. '□', best track position; '×', fix position; '●', objective warning position; '⧗', JTWC warning position.

the objective technique still had a smaller average warning position error (20.2 n mi, standard deviation 11.5 n mi) compared to JTWC (average position error 26.1 n mi, standard deviation 20.2 n mi). Unfortunately, this skill in looping situations does not hold for all of the cases. Six other storms (Pamela during 1982 and Percy, Lex, Abby, Bess and Sperry during 1983) had a loop sometime during their lifespan. Only three of the looping storms (Nelson, Sperry and Bess) had smaller warning position errors during the looping phase when using the objective scheme. In each of these three storms, there was relatively slow movement through the loop. In the remaining cases, the objective technique based on CLIPER did not handle the rapid direction changes associated with a tight loop.

The use of the objective technique should not be ruled out in all non-climatological situations. As an example, the entire lifespan of Tropical Storm Sperry (1983) consisted of a clockwise loop in the region east of the Philippines (Fig. 3.5). Once again the slow speeds throughout the majority of the loop allowed the objective technique to produce smaller warning position errors than JTWC (see Table 13).

The TDO may have to adjust the objective warning position when additional knowledge not reflected in the fix positions is available. Such a situation appeared for the warning position of Typhoon Thad on 00 GMT 23 August 1981. The objective technique relied on two satellite fixes shown in Fig. 3.6 Although the resulting objective warning position was consistent with the prior storm track, the position error was 105 n mi compared to a JTWC error of 30 n mi Evidently, the TDO had more information than the two satellite fixes provided.

In summary, the 30-storm sample provides a fair representation of the various forecasting scenarios including

entirely on BT positions were the most accurate. As in the initial position evaluation above, the 24-h forecasts based on the objective warning positions compared favorably with those based on JTWC warning positions during 1981 and 1982. The average 24-h forecast error for the objective scheme was 122 n mi for 1981 and 113 n mi for 1982. This can be compared to 127 n mi for 1981 and 111 n mi for 1982 based on JTWC's warning positions. The percentage of win and tie category storms was 55% in 1981 and 60% in 1982. However, only 20% of the storms during 1983 had better forecasts from the objective warning positions. According to the Student-t scores in Tables 14 - 16, none of the differences between the objective technique forecast errors and those of the JTWC were significant at the 95% confidence level. The standard deviations in Tables 14 - 16 indicate the 24-h forecasts based on the objective warning positions were slightly more erratic for 1982 (65 n mi) and 1983 (66 n mi) compared to forecasts from JTWC warning positions during 1982 (62.9 n mi) and 1983 (60 n mi)

The initial position error categories (Tables 11 - 13) are compared in Table 10 to the 24-h forecast position categories from Tables 14 - 16. Optimally, all storms in the win category of the initial position evaluation would be expected to result in a win category in the 24-h forecast position evaluation. It was not expected that storms with initial position losses would result in 24-h forecast position wins. As indicated in Table 10, most of the storms do fall in the win-win and loss-loss categories. However, two cases (Super Typhoon Marge (1983) and Typhoon Ken (1982)) fall in the loss-win category, i.e. an initial position error loss for the objective technique results in a 24-h forecast position win. Both storms were characterized by recurving tracks. A relatively large number of storms (6) with a win in terms of smaller initial position errors

and smaller 24-h forecast errors from those warning positions (Table 18). Objectively initiated CLIPER forecasts performed better from 12 GMT 31 October through 12 GMT 02 November 1983 (warnings 5 - 13, Table 18) while Marge was in the formative stages (< 65 kt) and then again from 18 GMT 03 November through 00 GMT 05 November 1983 (warnings 18 - 23, Table 18) during the initial stages of recurvature. In both periods, Typhoon Marge was about to make a major course change. In this case, the JTWC warning positions fell on the wrong side of the turn as shown previously in Fig. 3.7 and the corresponding CLIPER track departs significantly from the actual storm movement.

The characteristics of Tropical Storm Winona (1982) and Typhoon Dot (1982) are very similar in both time of occurrence (one month apart) and storm track (Typhoon Dot track approximately 5° north of Tropical Storm Winona). In both storms, the average initial position error evaluation resulted in a tie between the objective technique and the JTWC procedure (Winona, 22 n mi; Dot, 20 n mi). In the 24-h forecast evaluation, JTWC's warning positions resulted in smaller forecast error for Tropical Storm Winona (99 n mi compared to 110 n mi for the objective scheme). However, the objective technique's initial positions provided a superior forecast position error for Typhoon Dot (93 n mi compared to 105 n mi for forecasts from the JTWC warning positions).

C. SENSITIVITY TO STORM INTENSITY

The objective warning position errors or the corresponding 24-h forecast errors are examined for sensitivity to storm intensity. The 30-storm data base is stratified into storms of >130 kt (Super Typhoon), >65 kt (Typhoon) and <65 kt (Tropical Storm and Depressions). It should be noted

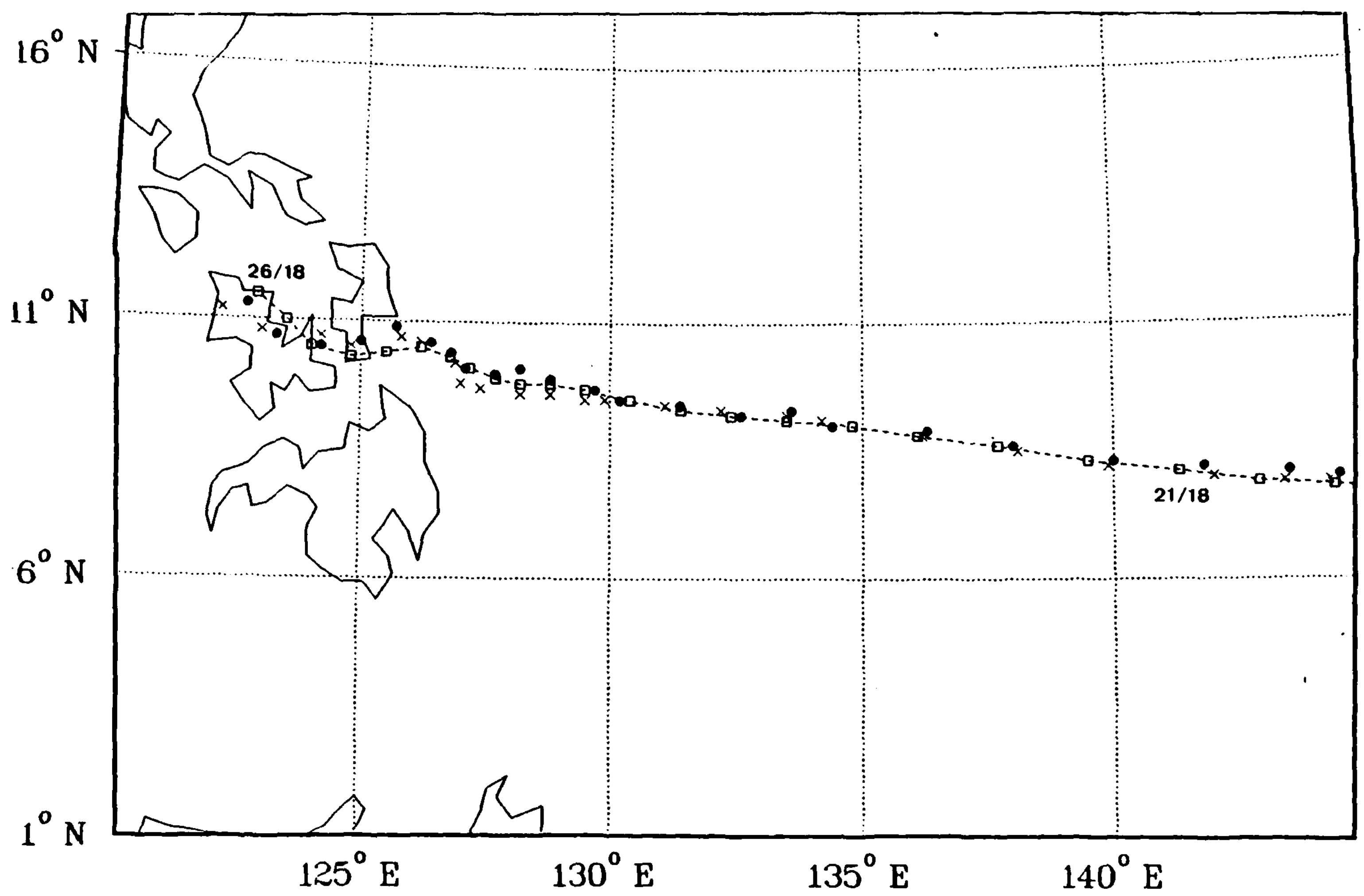

Fig. 3.3 Track of Typhoon Nelson (1982) from 21 March through 26 March. '□', best track position; '×', JTWC warning position; '●', objective warning position.

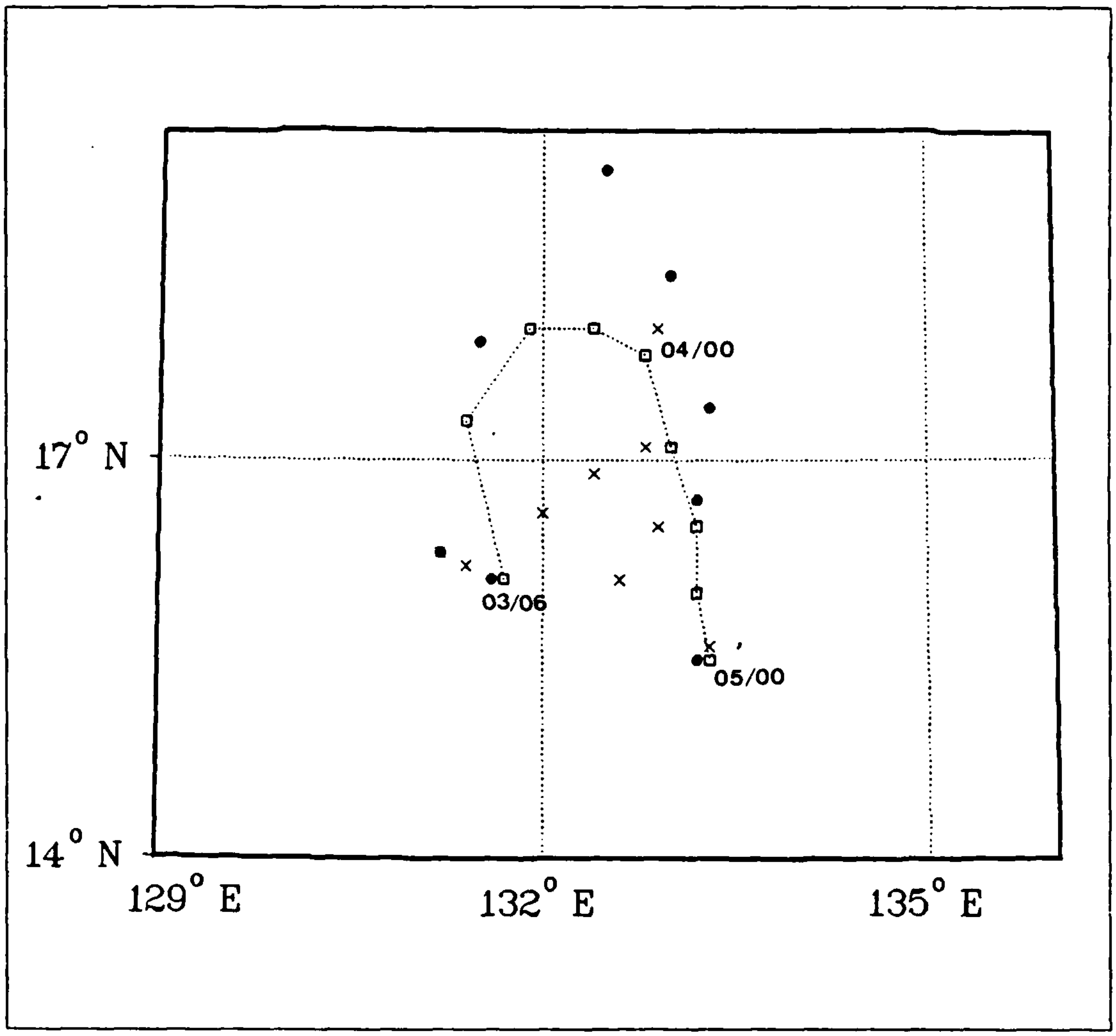

Fig. 3.5 Overall track of Tropical Storm Sperry (1983) from 03 December through 05 December. '□', best track position; '×', JTWC warning position; '●', objective warning position.

TABLE 10

Summary of 24-h forecast error category (win, tie, loss) versus initial position error category.

		24-h Forecast Category		
		WIN	TIE	LOSS
Initial -	WIN	7	2	6
Position -	TIE	2	0	3
Category	LOSS	2	0	7

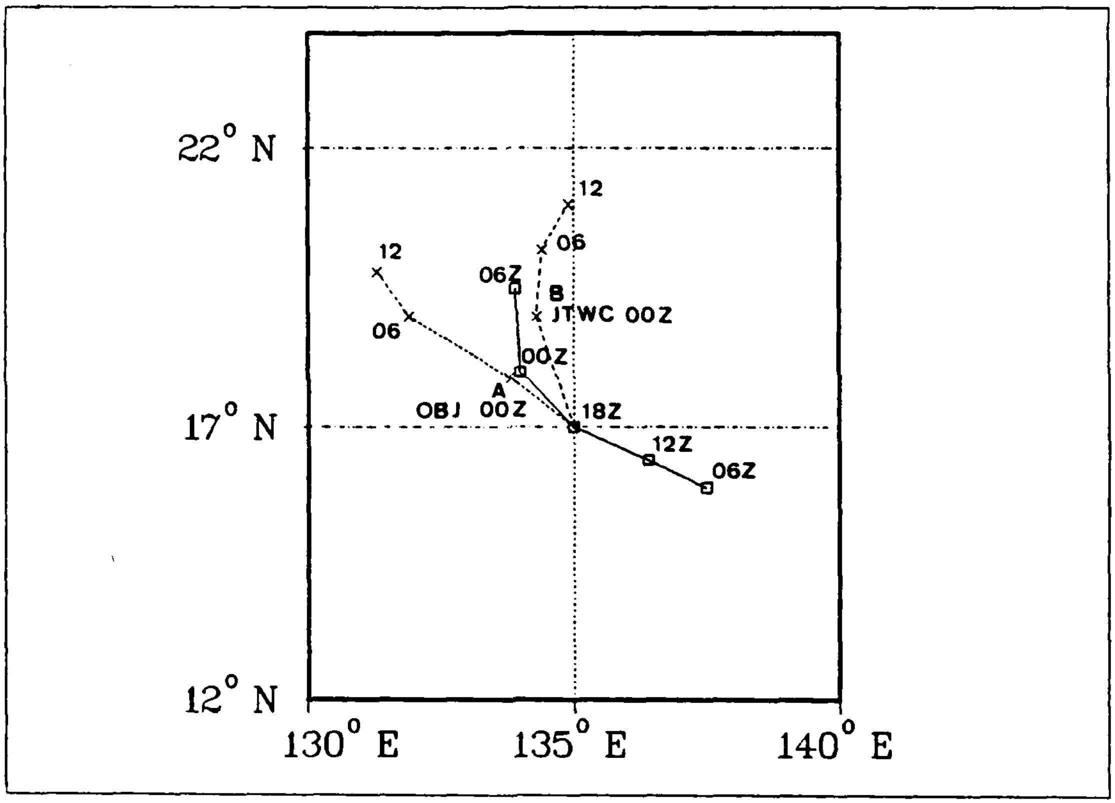

Fig. 3.7 Example of a larger forecast error from a warning position (A) that is more accurate than the official position (B).

TABLE 13

Summary of warning position errors (n.mi.) for JTWC (JT) and objective (OBJ) for the independent sample storms during 1983. Entries are similar to Table 9.

Storm	No. of Warnings	Avg. JT	Avg. OBJ	Std. Dev. JT	Std. Dev. OBJ	WTL	T
TY Tip	17	13	12	12	8	W	-.08
TS Ben	12	17	34	8	23	L	2.35*
STY Forrest	31	10	15	6	10	L	2.25*
TS Georgia	13	10	19	8	11	L	2.31*
TY Lex	17	18	18	13	15	T	-.01
TY Percy	24	22	27	22	13	L	1.01
TS Sperry	9	34	30	29	23	W	-.28
TS Thelma	15	32	25	33	13	W	-.61
Total	138						
Weighted Average		18	21	15	13		

* Difference between the objective error and JTWC official error is significant at 95% confidence level

TABLE 14

Summary of 24-h forecast errors (n.mi.) from CLIPER initiated with best track (BT) position, JTWC (JT) and objective (OBJ) warning positions for the 1981 storms.

Storm	No. of Warnings	Avg. BT	Avg. JT	Avg. OBJ	Std. Dev. BT	Std. Dev. JT	Std. Dev. OBJ	WTL	T
TY June	16	70	110	76	39	46	54	W	-1.92
TS Roy	12	107	151	129	58	78	56	W	-.80
TY Clara	25	57	80	69	34	54	36	W	-.91
STY Elsie	25	99	109	114	71	78	82	L	.21
TY Hazen	33	114	139	139	52	56	57	T	.00
TS Jeff	10	185	247	226	47	70	63	W	-.69
TY Kit	31	90	115	116	51	55	63	L	.07
Total	152								
Weighted Average		97	124	117	51	61	59		

TABLE 17

Summary of 24-h forecast position errors statistics (n mi) for Typhoon Nelson

Wrng. No.	Best TracK	JTWC Wrng.	Obj. Wrng.	Obj-JTWC
6	82	158	130	-28
7	68	83	88	5
8	56	76	101	25
9	88	88	100	12
10	124	86	86	0
11	178	312	178	-133
12	214	199	228	29
13	183	251	262	11
14	142	232	198	-34
15	91	143	152	9
16	49	91	79	-12
17	52	57	71	15
18	65	81	56	-25
19	62	70	87	17
20	57	53	79	27
21	65	61	74	13
22	68	81	64	-17
23	72	48	80	31
24	65	42	77	35
25	58	47	88	41
26	88	40	88	48
27	123	78	111	33
28	147	155	152	-3
29	121	126	153	27
30	77	122	116	-6
31	131	121	147	26
32	122	147	151	4
33	165	84	131	47
34	217	93	175	82
35	50	113	134	21
36	9	22	44	22
37	64	92	71	-22
38	23	42	42	0
39	41	54	45	-9
40	88	88	99	11
41	114	138	126	-12
42	140	233	188	-45
43	164	200	264	64
44	147	239	208	-32
45	119	103	163	60
46	127	117	158	42
47	125	122	156	34
48	90	105	118	13
49	72	65	106	40
50	82	60	133	73
51	191	85	127	42
Avg. Disp.	102	111	124	
Std. Dev.	50	65	54	

IV. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

An objective technique for determining the warning position of a tropical cyclone has been developed and shown to be a viable forecasting "tool" for the tropical cyclone forecaster. The thought processes of the TDO have been synthesized by the objective method of generating the "working best track" and future 24-h storm track, and the inclusion of the spatial and temporal weighting factors. This technique provides a consistent "first-guess" for the inexperienced forecaster (Morford, 1979) or a first step in an objective format (Simpson, 1971; Elsberry, 1984) for forecasting tropical cyclone movement. Compared to the JTWC warnings, the three year (1981 - 1983) sample indicates slightly more accurate and consistent warning positions from the objective scheme. On a storm-by-storm basis, 21 of the 30 storms had either improved or comparable warning position errors.

JTWC's method of blending the -6-h forecast positions from the objective aids with the latest fix information to determine the warning position, which was initiated in 1983 (Sandgathe, 1985), is similar in principle to this objective technique. During 1983, JTWC's method resulted in a smaller average warning position error. However, the objective technique still provided a more consistent position as indicated by the smaller standard deviation.

Nine of the 30 storms tested had larger warning position errors than JTWC. Of these nine, five storms either looped or departed significantly from climatological tracks. It is these difficult forecasting scenarios in which the TDO

model is readily compatible to desk-top computers and provides a fast, interactive forecasting model for the TDO. Optimally, the TDO will be able to quickly generate and evaluate a revised "working best track", warning position and short-term forecast track every time new fix information is received.

B. RECOMMENDATIONS

The CLIPER regression coefficients were derived for a limited time and space domain. New coefficients should be derived for a sample that includes JTWC's entire area of responsibility. CLIPER contains no synoptic field information or physical interpretations. Dynamic models such as the One-way (Interactive) Tropical Cyclone Model (OTCM) or the Nested Tropical Cyclone Model (NTCM) incorporate both synoptic data and physics and I would recommend that the objective scheme be coupled with each of these dynamic models to determine which pairing results in the greatest reduction of both warning position error and forecast position error. Finally, a real-time study of the objective scheme utilizing fix information and official JTWC warning positions should be conducted as a follow-on to this study.

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